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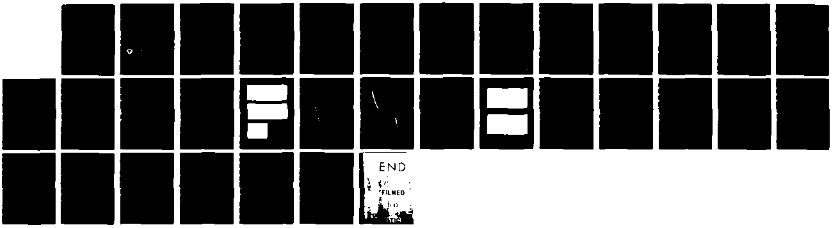

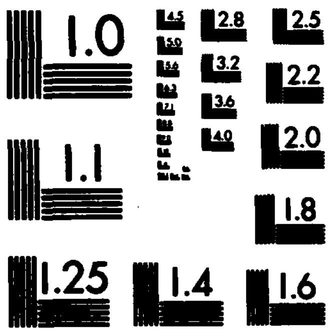

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TECHNICAL REPORT ARBRL-TR-02522

A TWO-DIMENSIONAL NUMERICAL STUDY OF DETONATION PROPAGATION BETWEEN MUNITIONS BY MEANS OF SHOCK INITIATION

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Computations of the flow field resulting when a munition is detonated adjacent to an identical neighbor have been made using the two-dimensional, eulerian, reactive hydrodynamic computer code, 2DE. The code was used to predict the effects of donor initiation site, interround separation distance, and shielding. The results indicate that a very complicated flow field is produced; that far-side initiation of the donor represents a worst case; that, for rounds separated only by an air space, the shock initiation hazard is

(continued)

20. ABSTRACT (continued)

maximum at an intermediate interround separation; that even very thin plastic shields which fill the space between the rounds are remarkably effective in reducing the shock initiation hazard; and that when the explosive sensitivity is sufficiently reduced the acceptor is no longer initiated by buildup of the principal shock. The potential usefulness of 2DE in predicting shock initiation has been evaluated.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

Shock initiation of the explosive charge is a major mechanism by which detonation propagates from round to round (donor to acceptor) in a munition store. Prevention of detonation propagation is a main thrust toward reducing the vulnerability of stored ammunition.[1-3] With the availability of hydrodynamic computer codes which incorporate models for the shock initiation of high explosives and in order to obtain a better understanding of the phenomenon of round-to-round propagation of detonation, including the effects of pertinent parameters on vulnerability, we have undertaken a numerical study using a two-dimensional analog of the problem. The two-dimensional code used is 2DE, which was developed at the Los Alamos National Laboratory and incorporates the Forest Fire model for shock initiation of explosives. This tool was used to determine the effects on sensitivity of such parameters as donor initiation site; interround spacing; shield configuration, thickness and material; as well as explosive sensitivity. In these computations, we have restricted our attention to those cases in which the propagation mechanism is classical shock initiation and have explicitly excluded other mechanisms which may be active in actual cases.

II. PROBLEM DESCRIPTION

The two-dimensional analog of the interround propagation problem used in our computations is illustrated in Figure 1. The model consists of a donor round, in which detonation is initiated, and an acceptor round which responds to the loading applied by the donor. The donor may be initiated at any of a number of sites, the interround separation distance and the casing thickness may be varied, various shields may be placed between the rounds, and the sensitivity of the acceptor explosive fill may be altered.

We have considered initiation sites at the center and far side of the donor round and interround separation distances, ΔR, of up to one round radius (although actual rounds may begin to break up into fragments before expanding this far and this effect is not included in the hydrodynamic model). The dimensions used are representative of the 105-mm projectile (R_0 = 52.5 mm) with a casing thickness, r, of 8 mm. The effects of different thicknesses, h, of Plexiglas shielding were considered. Different shield materials were also studied. Composition-B (comp-B) was used as the donor explosive in all our

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[1] *Howe, P. M., "The Phenomenology of Interround Communication and Techniques for Prevention," Ballistic Research Laboratory Technical Report ARBRL-TR-02048, March 1978 (AD A054373).*

[2] *Howe, P. M. and Collis, D., "Effectiveness of Plastic Shields in Prevention of Propagation of Reaction Between Compartmentalized Warheads," Ballistic Research Laboratory Memorandum Report ARBRL-MR-02827, April 1978 (AD B027466L).*

[3] *Howe, P. M., "An Approach to the Development of Hardened Munitions, Part A - Warheads," Ballistic Research Laboratory Special Publication ARBRL-SP-00010, June 1979 (AD B038925L).*

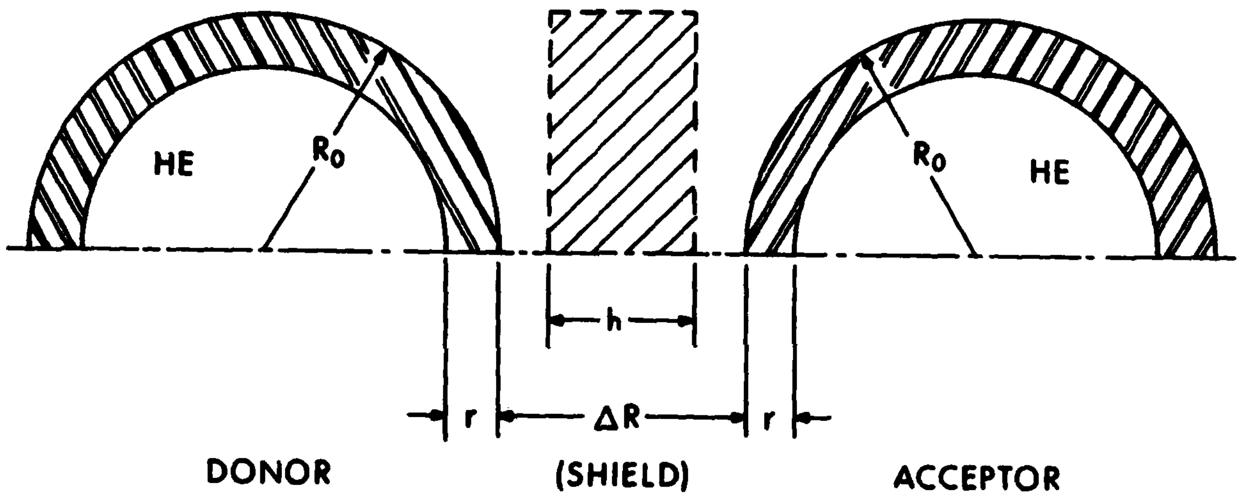

Figure 1. Geometry used in Interround Detonation Propagation Computations

computations. Except for our studies of explosive sensitivity it was also used as the acceptor explosive. In order to assess the effects of reducing sensitivity we considered an acceptor filled with TATB.

We often found it instructive to observe the loading on the acceptor with an inert fill and we investigated the effects of initiation site, interround spacing and, in one case, shielding, suppressing the Forest Fire model in the computations. Reactive acceptors were considered for study of shielding effectiveness and explosive sensitivity. In general, 2DE appears to predict shock pressures which are considerably higher than those measured experimentally or predicted by other computational means(a problem which we have addressed). For this reason, we were unable to suppress initiation of the acceptor and had to rely on other measures of sensitivity reduction to assess the effects of parameter changes. In the case of inert acceptors, observation of p(t) and $\int p^2(t)dt$ associated with the arrival of the principal shock at the explosive-casing interface at the symmetry plane were made and were used to characterize acceptor response. The latter parameter is a measure of the energy available for hot spot formation in the shock. In the case of reactive acceptors, buildup to detonation was followed in the distance-time and shock pressure-time planes, except when the buildup occurred off the symmetry plane due to shock reflection at the casing in reduced sensitivity acceptors.

III. DESCRIPTION OF 2DE

The 2DE code was developed at the Los Alamos National Laboratory and is a two-dimensional, eulerian reactive code.[4-5] It requires constant grid spacing throughout the computational region and provides only linear artificial viscosity. For our problem, it was necessary to describe the initial geometry using rectangular elements. Thus, the circular shapes are not perfectly represented. The code makes use of the C-J volume burn model to account for detonation in the donor and the Forest Fire model to describe buildup to detonation in the acceptor when desired.

IV. DISCUSSION OF RESULTS

General Features of the Flow Field with Inert Acceptors

The flow field determined in the two-dimensional computations with inert acceptors is most easily observed in the distance-time plane, where the distance is measured along the symmetry plane. Shock patterns produced in several configurations are illustrated in Figure 2.

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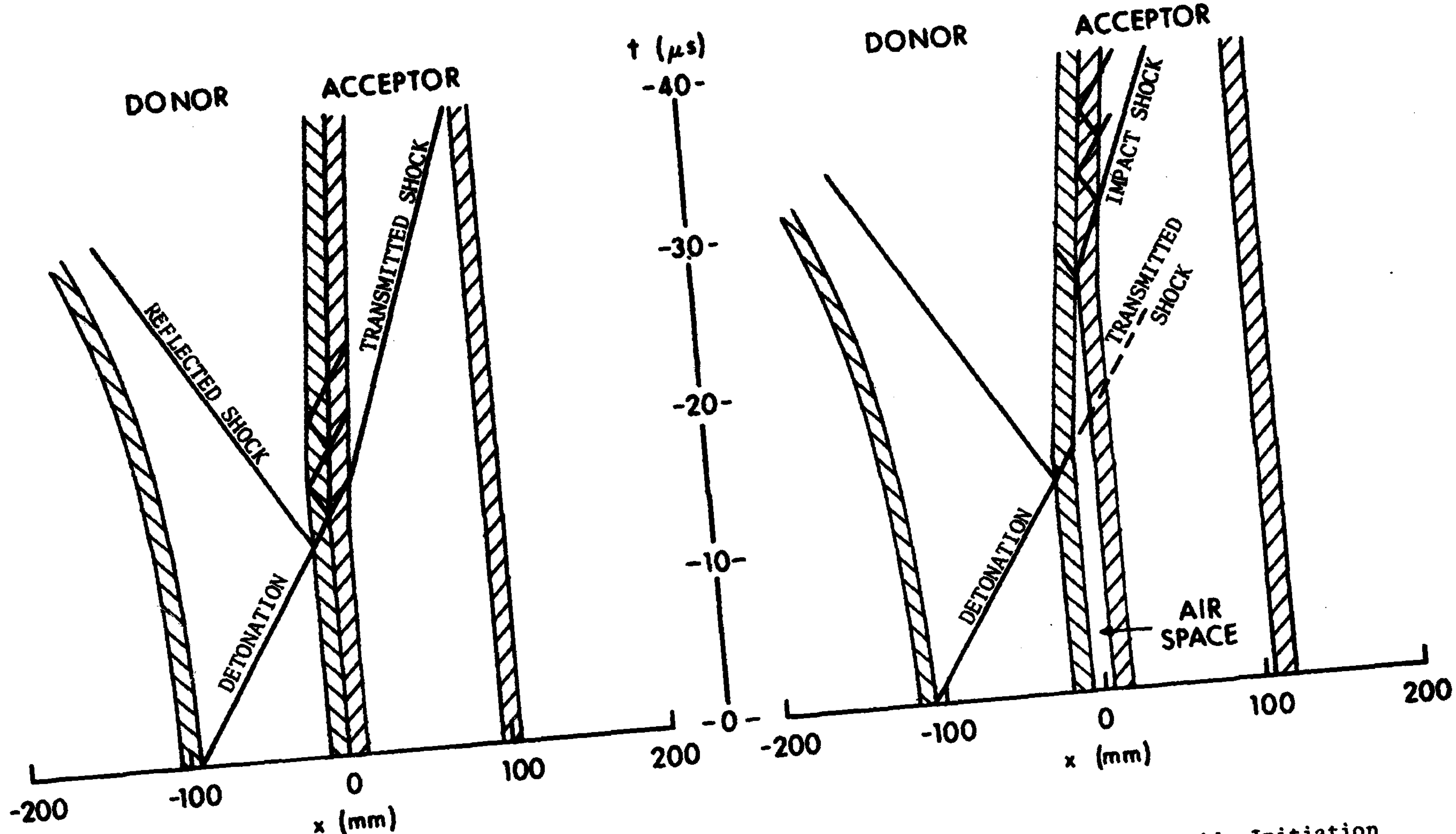
[4] *Mader, C. L., Numerical Modeling of Detonations, University of California Press, 1979.*

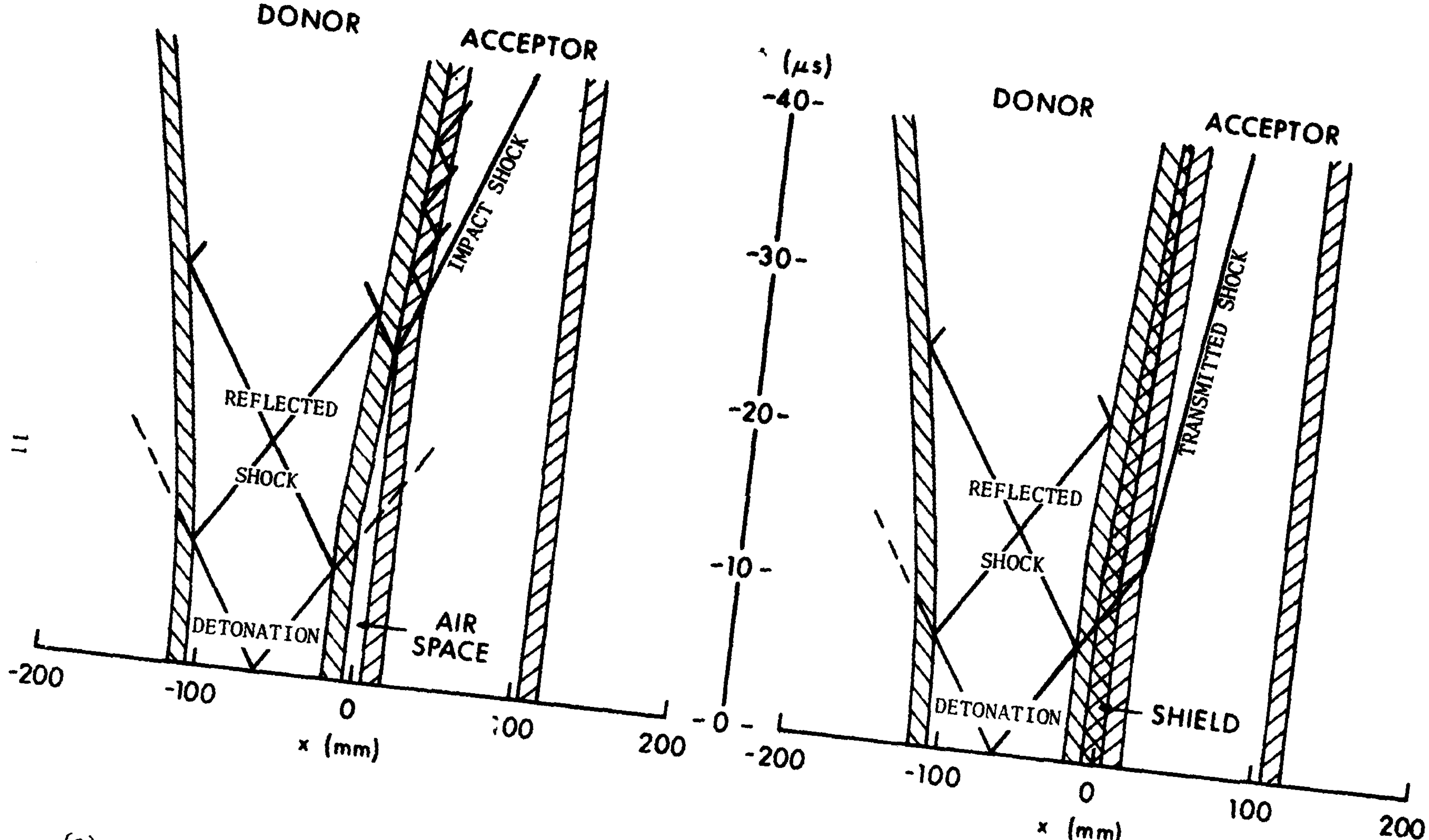
[5] *Kershner, J. D. and Mader, C. L., "2DE: A Two Dimensional Continuous Eulerian Hydrodynamic Code for Computing Multicomponent Reactive Hydrodynamic Problems," Los Alamos Scientific Laboratory Technical Report LA-4846, March 1972.*



(a) Rounds in Contact, Far-Side Initiation

(b) Separated Rounds. Far-Side Initiation

Figure 2. Shock Patterns Produced with Inert Acceptors



(c) Separated Rounds, Center Initiation

(d) Shielded Rounds, Center Initiation

Figure 2. Shock Patterns Produced with Inert Acceptors (continued)

The shock patterns produced by far-side initiation of the donor with rounds in contact may be compared to those obtained with separated rounds in Figures 2a and 2b. In both cases, the detonation propagates smoothly across the donor from its far side. When the donor and acceptor are in contact, the principal shock propagating into the acceptor is directly transmitted from the initial detonation in the donor. When the donor and acceptor are separated, the principal shock is generated by the impact of the donor casing on the acceptor. The transmitted shock which has propagated across the air gap is quite weak (only about 0.1 GPa, depending on the distance travelled) and is insufficient to initiate the acceptor. In either case, shock reverberations in the donor and acceptor casings lead to multiple shock loading of the acceptor explosive. The principle shock may be readily identified by its strength and persistence, however, and this is the shock which builds to detonation in the reactive cases.

The shock patterns produced by center initiation with separated rounds is shown in Figure 2c. The principal difference between center and side initiation is the nature of the shock patterns in the donors. In the center initiation case, the detonation wave proceeds outward from the initiation site. When the detonation reaches the casing, one shock wave propagates through the shell wall and another is reflected back into the explosive products. The transmitted shock propagates through the donor casing, the air gap, the acceptor casing, and finally into the acceptor explosive. The reflected shock propagates back to the center of the donor, which is still an axis of symmetry with respect to donor shock propagation. Here it is reflected outward, producing a second diverging shock. In the meantime, the donor casing is accelerated outward until an impact with the acceptor casing occurs. At this point, strong shock waves are generated and propagate into the donor's detonation products as well as the acceptor explosive. Multiple shocks are observed due to reverberations within the casings. Generally, the first two of these shocks are of principal interest. The second shock is stronger than the first and overtakes it after a very short distance. At a particular interround separation distance, the casing impact will occur at the same time that the second diverging wave arrives at the outer surface. The reinforcement occurring in this event will produce especially severe shock loading in the acceptor. Except in the event of this reinforcement, far-side initiation is expected to produce stronger shocks in the acceptor than are observed for center initiation since the momentum of all the explosive products is directed generally toward the acceptor. Symmetry is absent for side initiation and no reflected divergent wave appears in the donor. The response upon impact is quite similar, however, just somewhat more severe.

Finally, the shock pattern produced by center initiation with a shield between the rounds is shown in Figure 2d. In this case, the shield completely fills the space between the round along the line of centers. The shock loading on the acceptor is similar to that for rounds in contact. The principal shock is again directly transmitted but its amplitude may be attenuated by the shield. Shock reverberations, although not shown in the figure, are still present.

Effects of Initiation Site and Interround Separation

The principal shock pressures and associated $\int p^2 dt$ values obtained from 2DE computations with inert acceptors are plotted versus interround separation for both center and far-side initiation in Figure 3. Each of these parameters

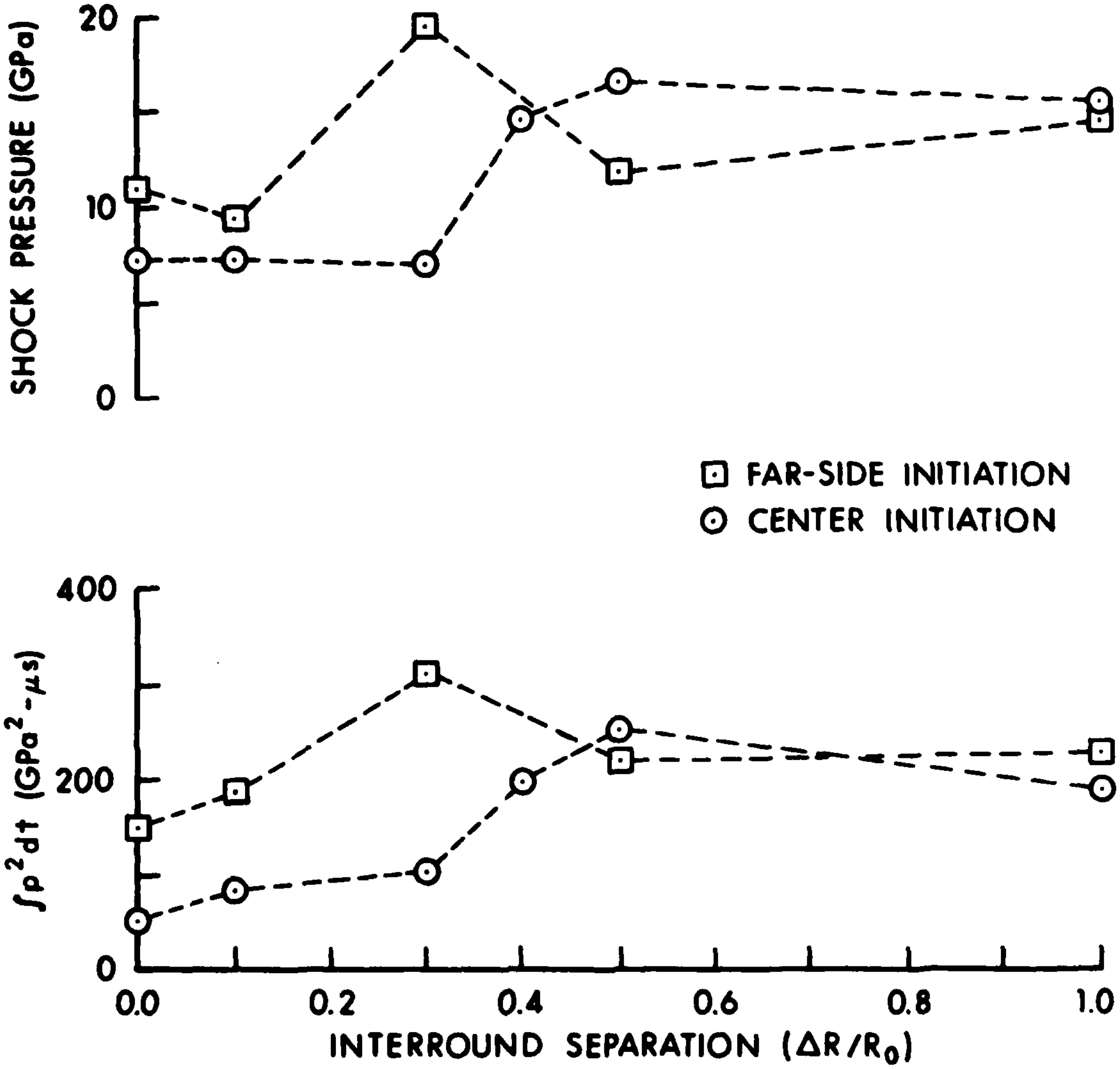


Figure 3. Effects of Initiation Site and Interround Separation on Shock Pressure and $\int p^2 dt$ in Inert Computations

appears to approach a common value at large separations. Reinforcement by the divergent shock in the donor occurs at an interround separation somewhere between 0.4 and 0.6 round radius (R_o). In this region, the initiation stimulus is only slightly more severe in the center initiation case. The results indicate that far-side initiation, which represents a more realistic scenario for the interround propagation of detonation, may be regarded as a worst case. The shock initiation hazard appears to be greatest when the interround separation is about 0.3 R_o.

Effects of Shielding

Continuing our study of inert acceptors, we made a single two-dimensional computation with an interround separation of one-tenth round radius (5 mm), a rectangular Plexiglas shield completely filling the space between the rounds, and a center initiated donor. The results of this computation may be compared to those for the similar case without the shield. In Figure 4, the pressure history just inside the acceptor casing in the first pure explosive cell is plotted for both cases. It should be noted that, due to the eulerian representation, it is necessary to periodically shift attention to a neighboring cell as the casing intrudes into the observed cell. This causes an artifical spike to be plotted. While the pressure of the initial shock is slightly higher in the shielded case, the pressure of the principal shock is significantly lower. We have also computed $\int p^2 dt$ including the first two shocks in each case and the unshielded case produces a much higher value. The results indicate a substantial reduction in sensitivity even with a very thin plastic shield.

The general sequence of events revealed with reactive acceptors is illustrated in the sequence of plots in Figure 5. Here pressure is plotted versus the two-dimensional physical plane of the problem at various times. Plotting of pressure in the steel casing has been suppressed for clarity. In Figure 5a at 4 μs, the donor round has been initiated at its far side and the detonation wave has begun to propagate across the round. In Figure 5b at 16 μs, the donor explosive has been completely consumed and a shock wave is being transmitted through the shield. In Figure 5c at 24 μs, the shock wave has propagated into the acceptor explosive. Shortly thereafter at 26 μs, the shock has begun to build in strength due to partial reaction of the explosive. This is illustrated in Figure 5d. Finally, the shock has grown to full detonation at 28 μs as shown in Figure 5e.

The way in which shielding influences the initiation process was assessed considering cases with reactive acceptors. Four computations have been completed with an interround separation of one-half round radius (25 mm), utilizing Plexiglas shields filling 50, 75, 87.5 and 100 percent of the space between rounds. The shock pressure history obtained in each case is plotted in Figure 6 as the shock builds to detonation. The histories for $h/\Delta R$ = 0.50, 0.75 and 0.875 are virtually identical while the shock produced at $h/\Delta R$ = 1.00 builds to detonation more slowly. When the space between the rounds is not completely filled, impacts occur at the symmetry plane and the shock enters the acceptor at a pressure of seven to ten GPa. Buildup to detonation occurs rapidly. When, on the other hand, the space is completely filled by the shield, normal impact is eliminated and the shock enters at a pressure of two to three GPa. Buildup then occurs

relatively slowly until the seven to ten GPa range is reached, after which buildup to detonation is rapid and parallels the stronger shock buildup. As we noted previously, these pressures are considerably higher than those we would expect to see and the detonation pressure is in excess of the C-J value.

We have also studied the buildup produced with shields of various thickness which completely fill the space between rounds. Here our interpretation of the results has been severely hampered by the failure to suppress sympathetic detonation of the acceptor. The buildup to detonation of shocks transmitted through these shields is shown in Figure 7. The variation in initial shock pressure is quite small and very little difference between cases is noticeable except for the thinnest shield which affords very little protection. The results appear to indicate that protection is optimized for shields between 0.4 and 0.75 round radii thick and shield performance is worse both above and below this thickness. However, results of this type provide a rather unsatisfactory representation of the sensitivity reduction to be obtained by this or any other parameter variation.

Shield materials considered include Plexiglas, teflon, tuballoy, steel, and aluminum. The results are presented in Figure 8. The order of effectiveness of these materials is consistent with the initial shock pressure they produce. The best results were produced by Plexiglas, while the denser metals (steel and tuballoy) performed poorly. The results for aluminum and teflon were in the intermediate range. Some experiments, however, seem to indicate that steel does provide considerable protection. This result does not appear consistent with the shock initiation mechanism and instances where steel shields have been effective may be cases in which other initiation mechanisms are active.

Since the shock pressure predictions of the 2DE computations are erroneously high and the Forest Fire model is activated prematurely, we were unable to predict protection of the acceptor with shielding. This is an unfortunate limitation since a determination of the shield thickness required for protection as a function of any parameter of interest would be more useful, particularly since the differences in initial shock pressure produced by shields of varying thickness are small.

Effects of Reducing Sensitivity

In one case, we replaced the comp-B in the acceptor with the less sensitive explosive, TATB. The results of those computations revealed that no buildup to detonation occurred along the symmetry plane as for comp-B. In this case, the shock wave propagates through the acceptor explosive without producing reaction as shown in Figure 9a. In the more remote portion of the acceptor, the shock propagates into a converging channel formed by the steel casing. The reflection which occurs at the point of interaction between the shock and the casing leads to increased pressures as shown in Figure 9b. This eventually leads to initiation of detonation at this point as shown in Figures 9c and 9d. Presumably, as the explosive sensitivity is further reduced, the initiation point, requiring higher pressure, would move around the casing to the far side and ultimately initiation would be entirely suppressed. The same result is expected for any explosive as the initiation stimulus is reduced. The normal reflection off the back of the shell casing will always produce significant pressures. It seems unlikely that initiations of this kind actually occur

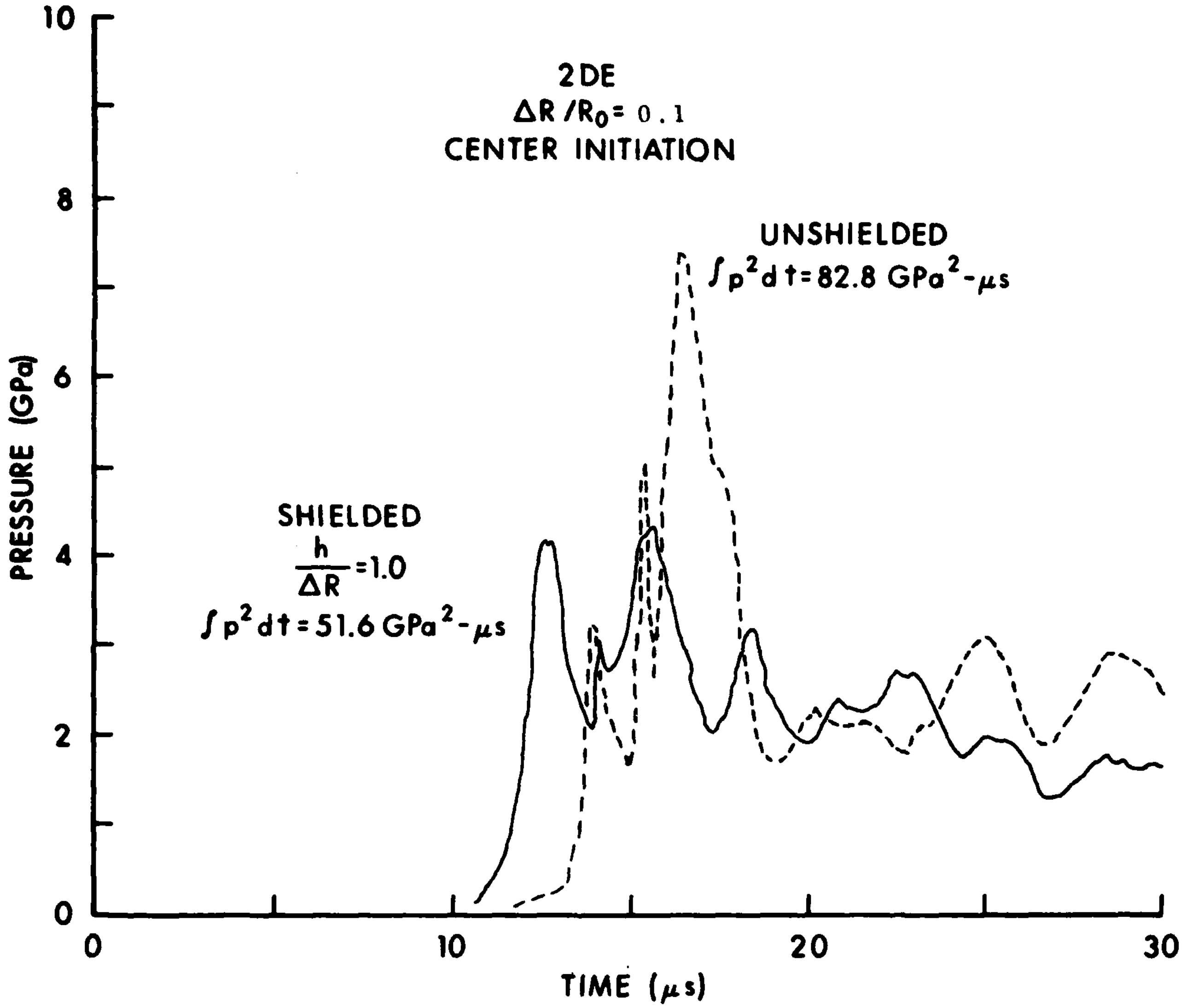


Figure 4. Effects of Shielding on the Shock Loading of an Inert Acceptor

(a) t = 4 μs (b) t = 16 μs

(c) t = 24 μs (d) t = 26 μs

(e) t = 28 μs

Figure 5. Sequence of Events in Interround Propagation of Detonation - Comp-B Acceptor

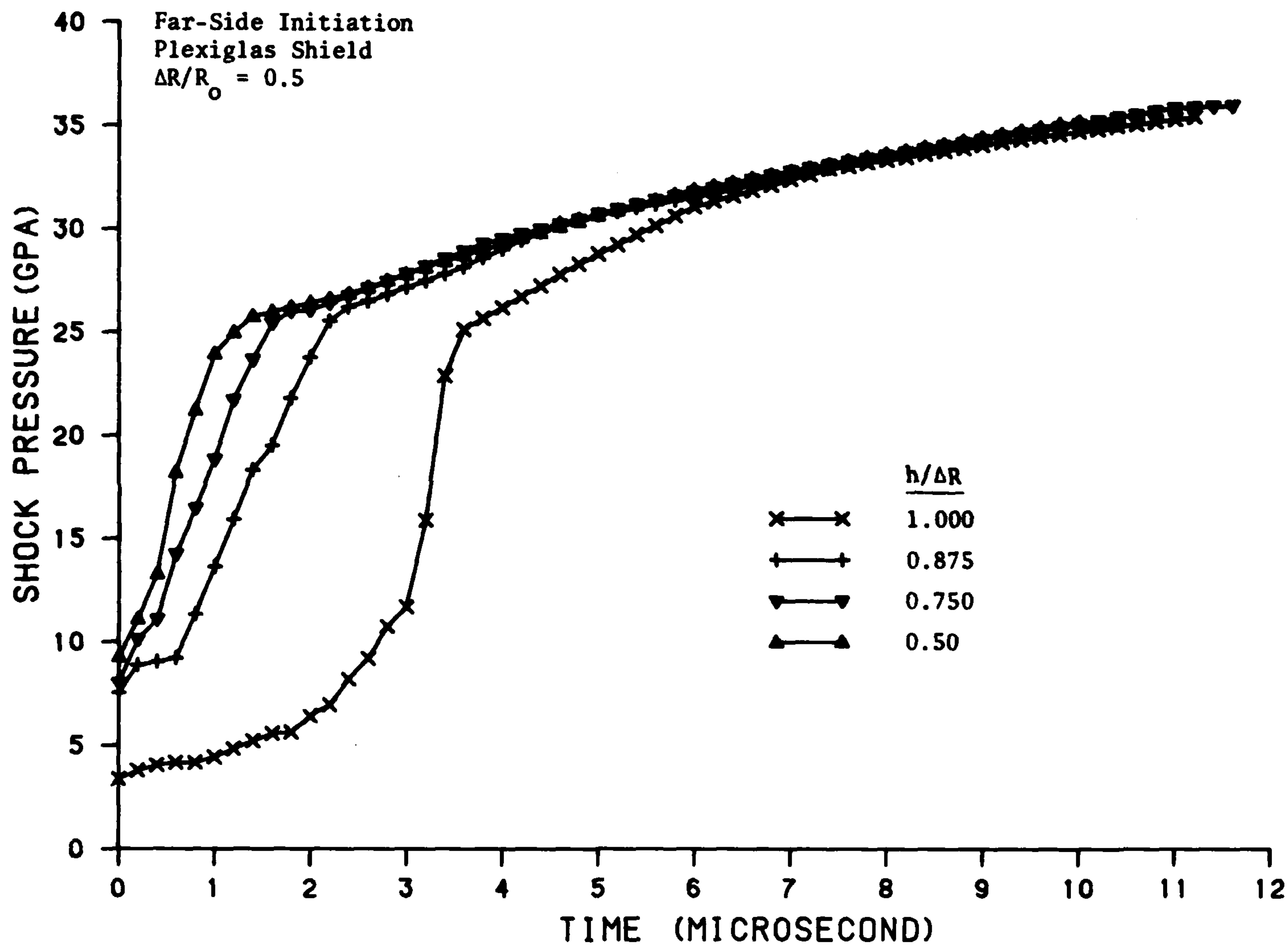


Figure 6. Effect of Shield Configuration on Shock Initiation

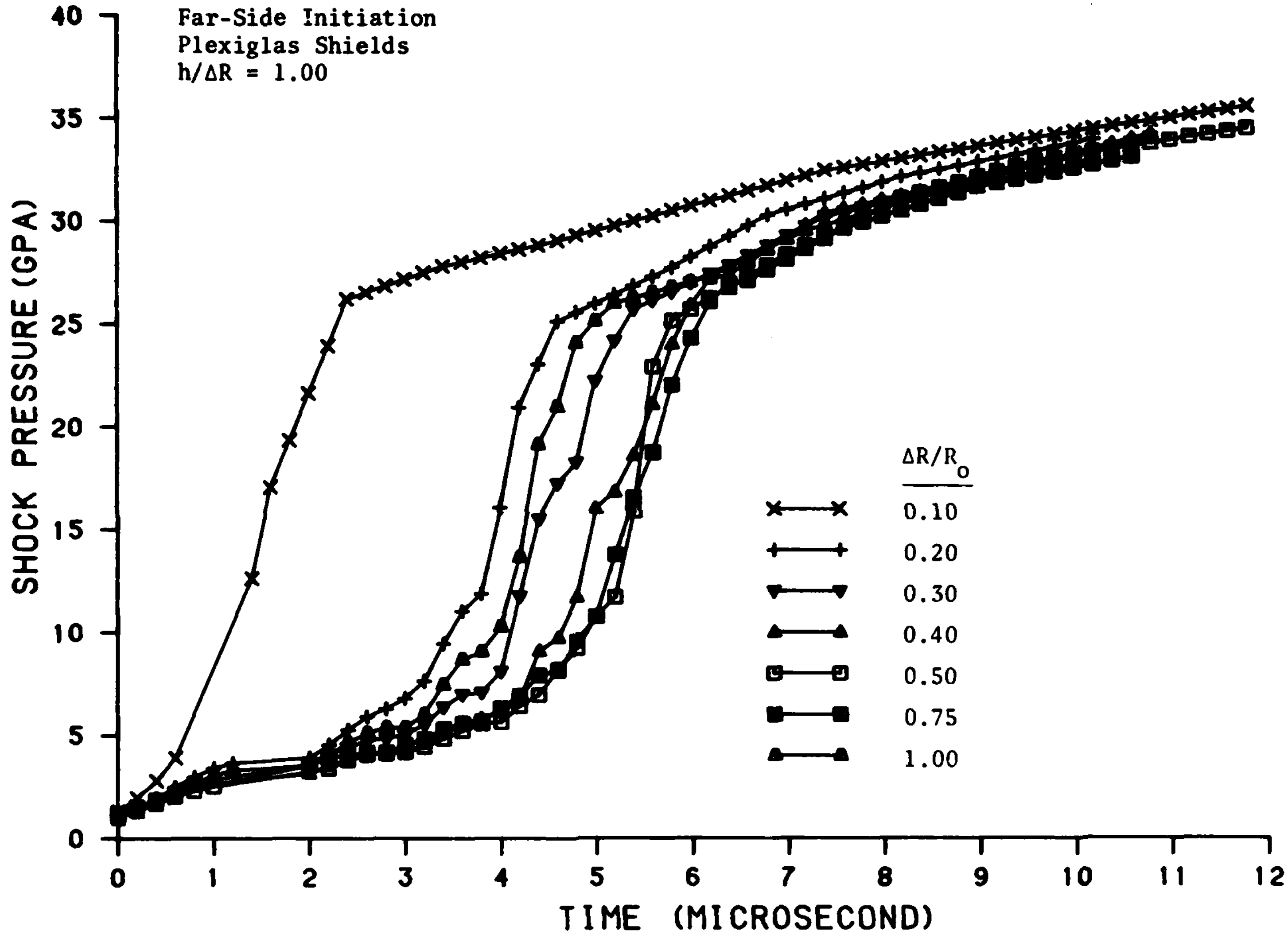


Figure 7. Effect of Shield Thickness on Shock Initiation

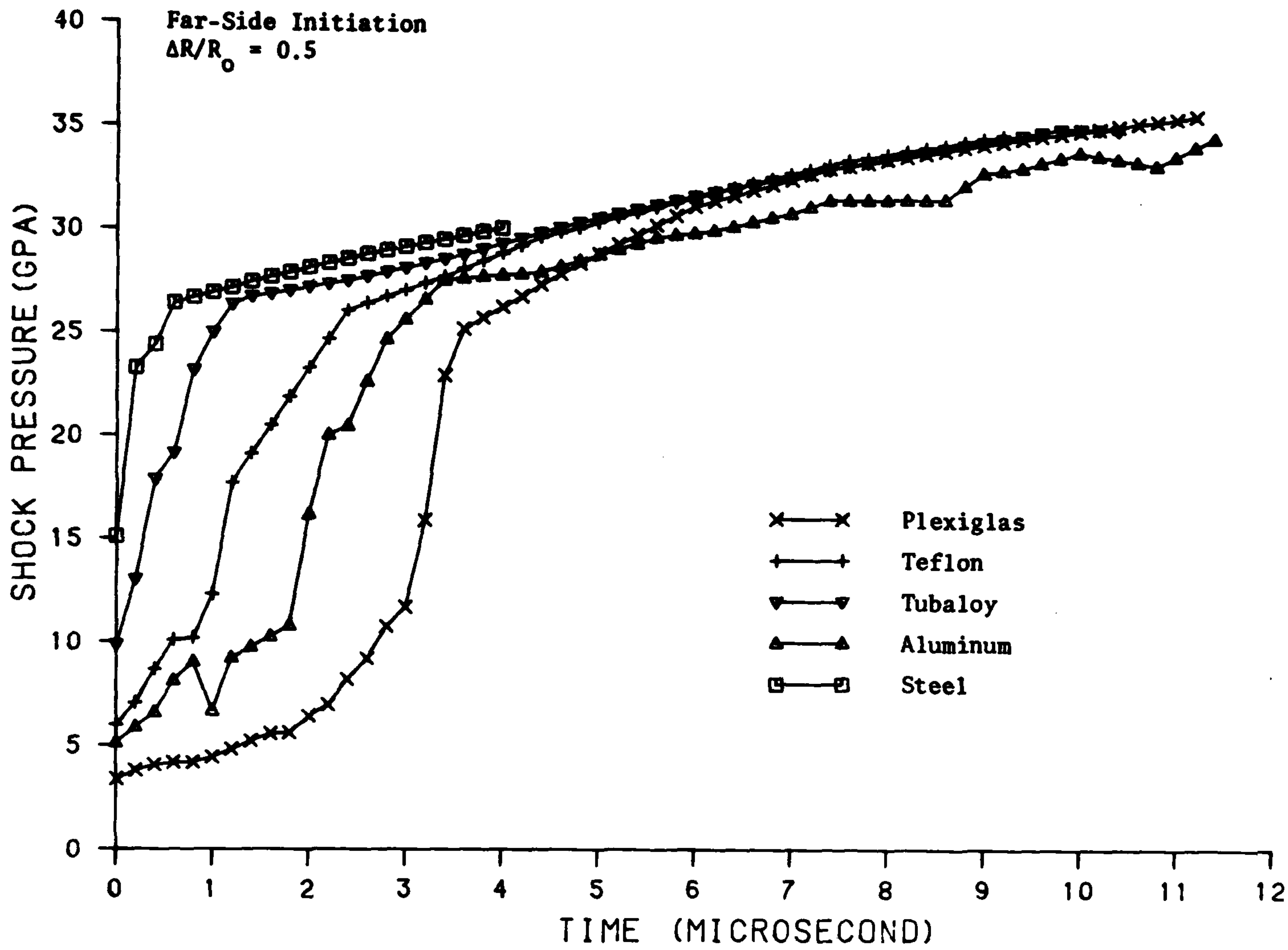
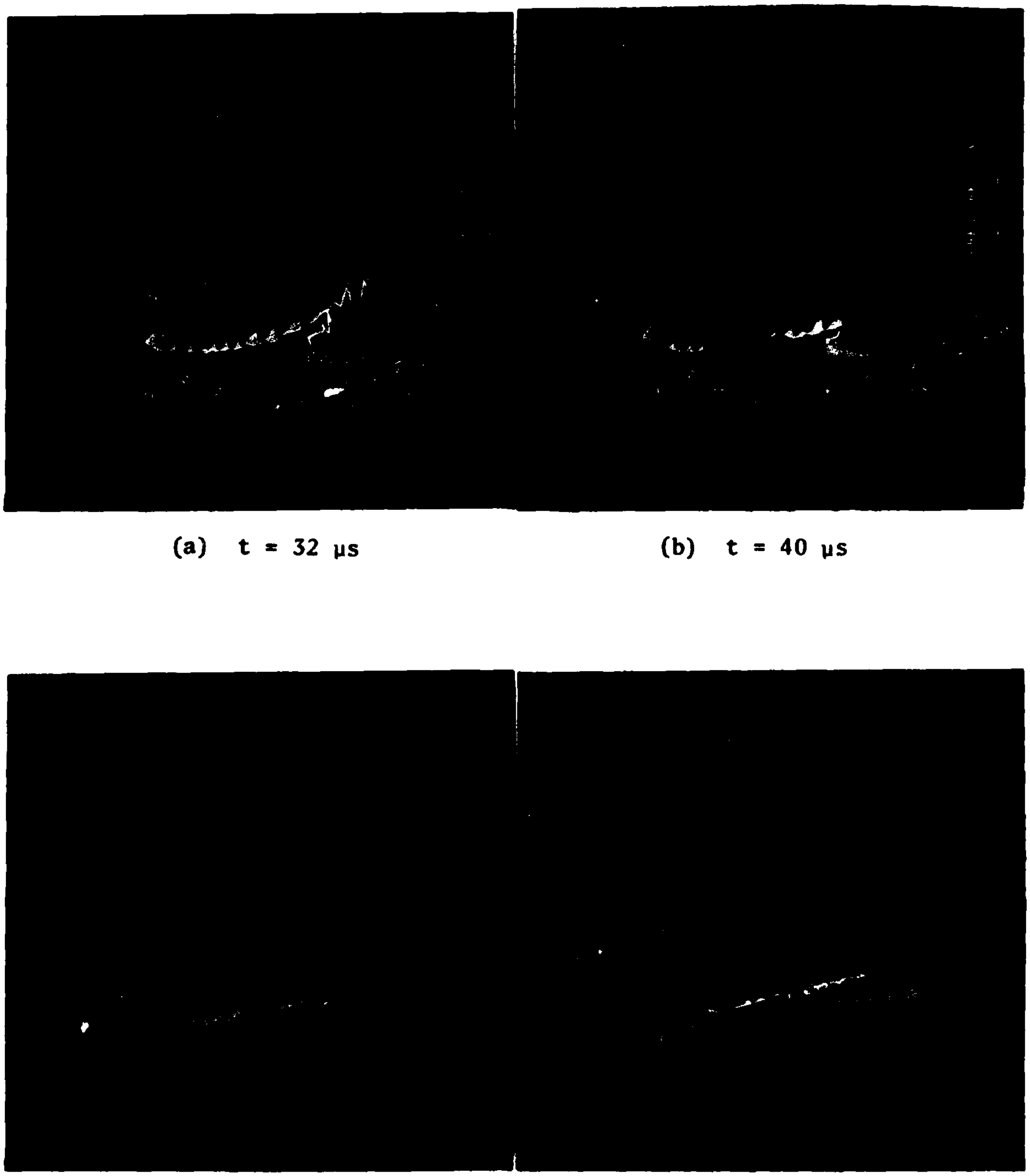


Figure 8. Effect of Shield Material on Shock Initiation



(a) t = 32 μs (b) t = 40 μs

(c) t = 46 μs (d) t = 50 μs

Figure 9. Sequence of Events in Interround Propagation of Detonation - TATB Acceptor

frequently since protection against them would be virtually impossible and successful shield designs have been developed. In this case, the reduction in sensitivity associated with the compaction produced by the principal shock wave may play a role which is not reflected in the present model.

V. EVALUATION OF 2DE

The principal advantage of 2DE is its incorporation of the Forest Fire model. Otherwise, the code lacks versatility in zoning capabilities and geometric representations. Its eulerian formulation does not facilitate following material history, which is important to the initiation process. Studies in which knowledge of the inert response alone is sufficient should certainly be carried out using a more sophisticated code. Use of 2DE is appropriate when a reactive model is required if the problems we encountered with high shock pressures can be eliminated. The reactive model is most useful when it properly predicts suppression of sympathetic detonation.

In running 2DE, we used artificial viscosity parameter values recommended by Los Alamos National Laboratory personnel who had successfuly employed the code for a number of years. We suspected that these values might be incorrect and be the cause of our shock pressure difficulties. Since the shocks in our problems are immediately followed by rarefactions, insufficient artificial viscosity and an attendant pressure overshoot are not readily apparent in the results. Therefore, we chose a sample problem in which we anticipated a flat, relatively long duration shock of known amplitude.

The problem, illustrated in Figure 10, is that of a 10 mm thick steel flyer plate striking a target (steel or comp-B) at 1,000 m/s. Figure 11a shows the pressure-distance profile obtained with the recommended viscosity and a steel target. The anticipated shock pressure is 21 GPa. The computational results oscillate about this value with a peak overshoot of about 7 GPa. With an increase in artificial viscosity of a factor of one hundred, a more adequate representation of the shock was obtained as shown in Figure 11b. Figure 12a shows results obtained with the recommended artificial viscosity and an inert comp-B target. Here a pressure overshoot of some 2 GPa occurs. This is sufficient to prematurely activate the Forest Fire model. As shown in Figure 12b, an increase of only a factor of ten in artificial viscosity is sufficient to effectively eliminate the overshoot. It should be noted that since 2DE uses linear artificial viscosity any viscosity increase results in additional smearing of the shock and intensifies requirements for fine zoning. Additional computations with reactive comp-B showed an increase in the critical velocity required for initiation from about 450 m/s to about 550 m/s when the artificial viscosity was increased.

With these corrected values of artificial viscosity in hand, we re-ran the shielding configuration which provided the best protection, a one-half round radius separation filled with Plexiglas. Shock buildup is compared with the original computation in Figure 13. The shock peak in the acceptor explosive initially appears at a slightly later time due to increased smearing. The pressure is slightly lower but detonation of the acceptor still results. The increased artificical viscosity appears to produce a better representation of the detonation with pressures closer to the C-J value of 29.4 GPa.

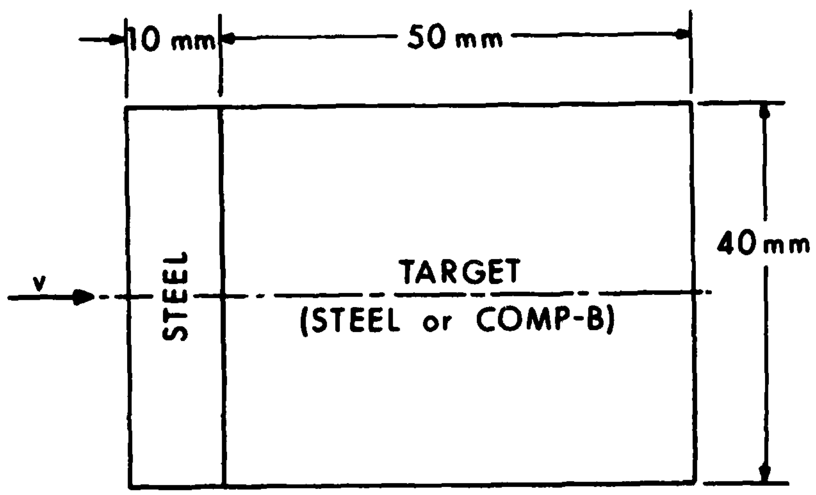
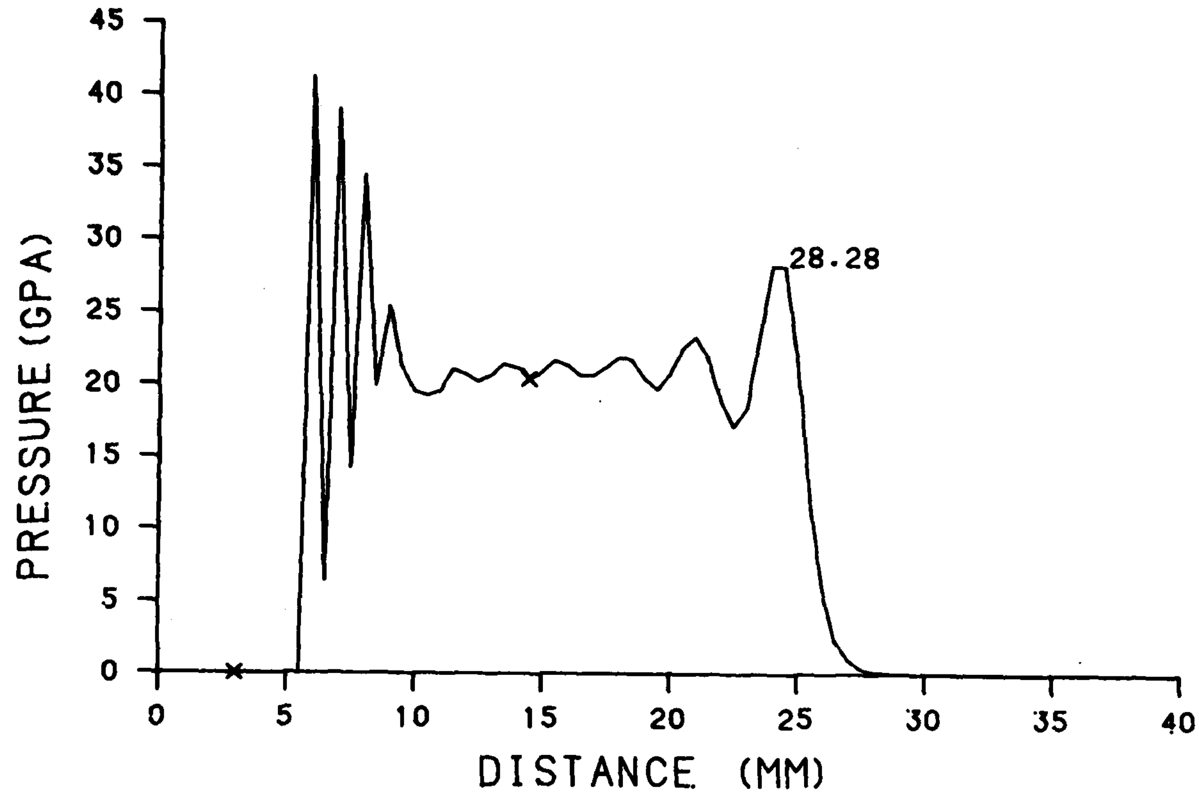
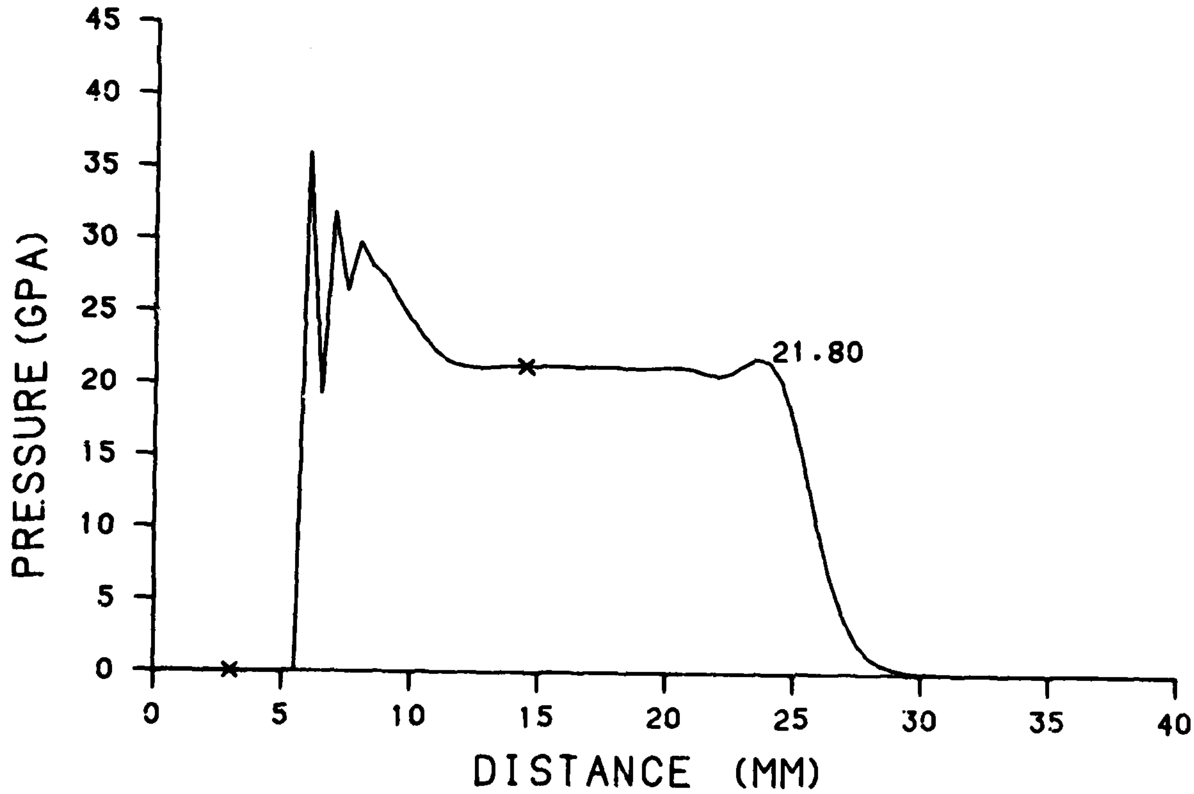


Figure 10. Test Problem Geometry

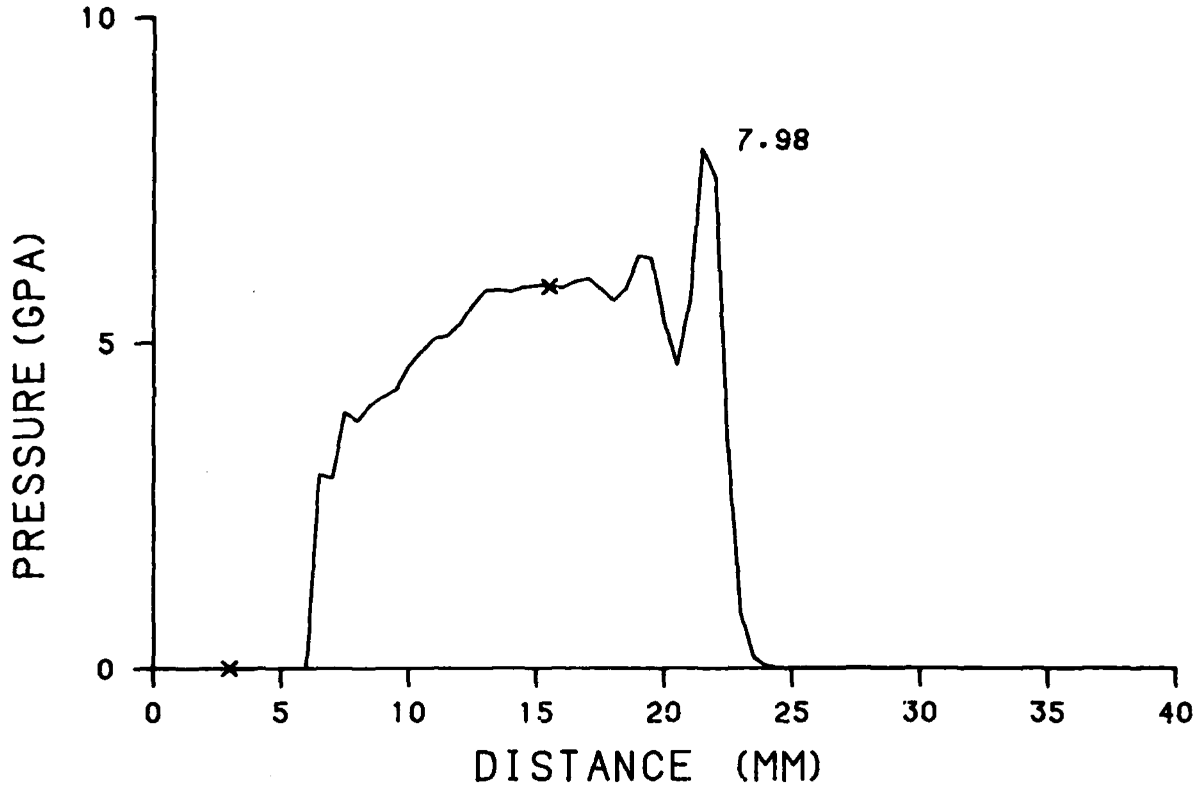


(a) Recommended Viscosity

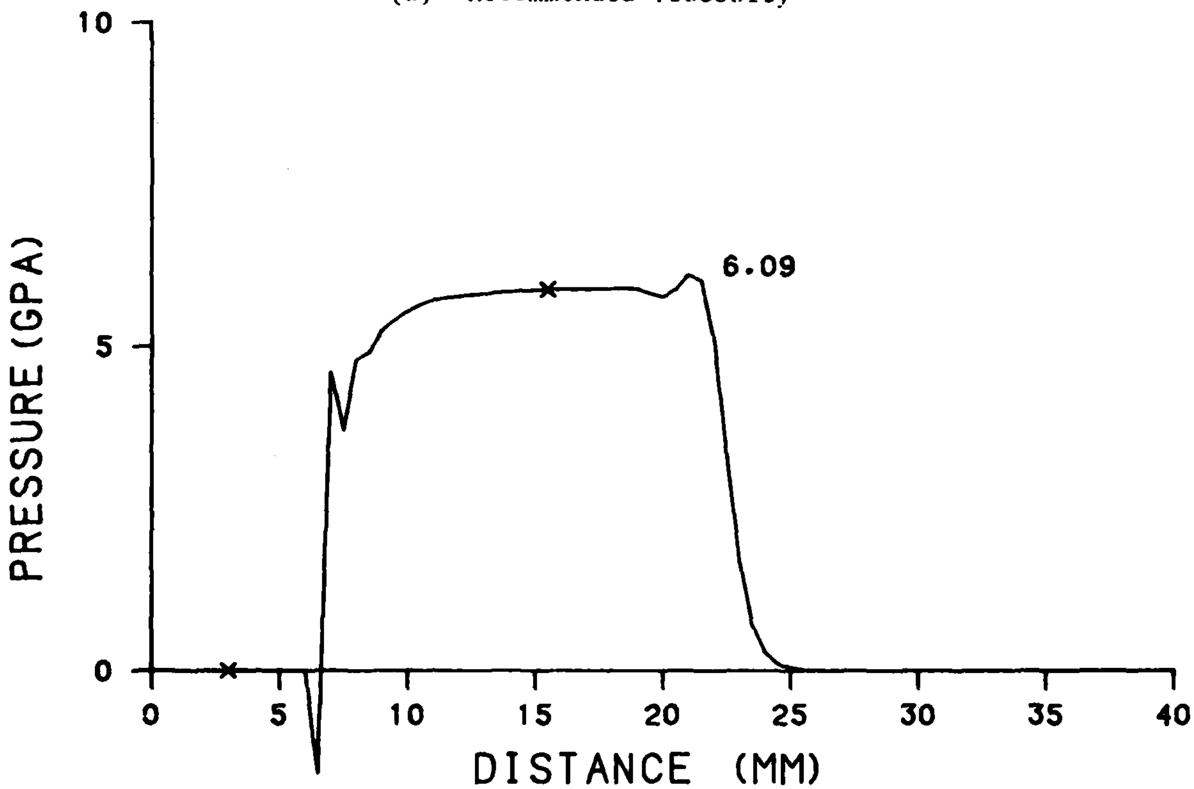


(b) 100X Recommended Viscosity

Figure 11. Effect of Increasing Artificial Viscosity - Steel Target



(a) Recommended Viscosity



(b) 10X Recommended Viscosity

Figure 12. Effect of Increasing Artificial Viscosity - Comp-B Target

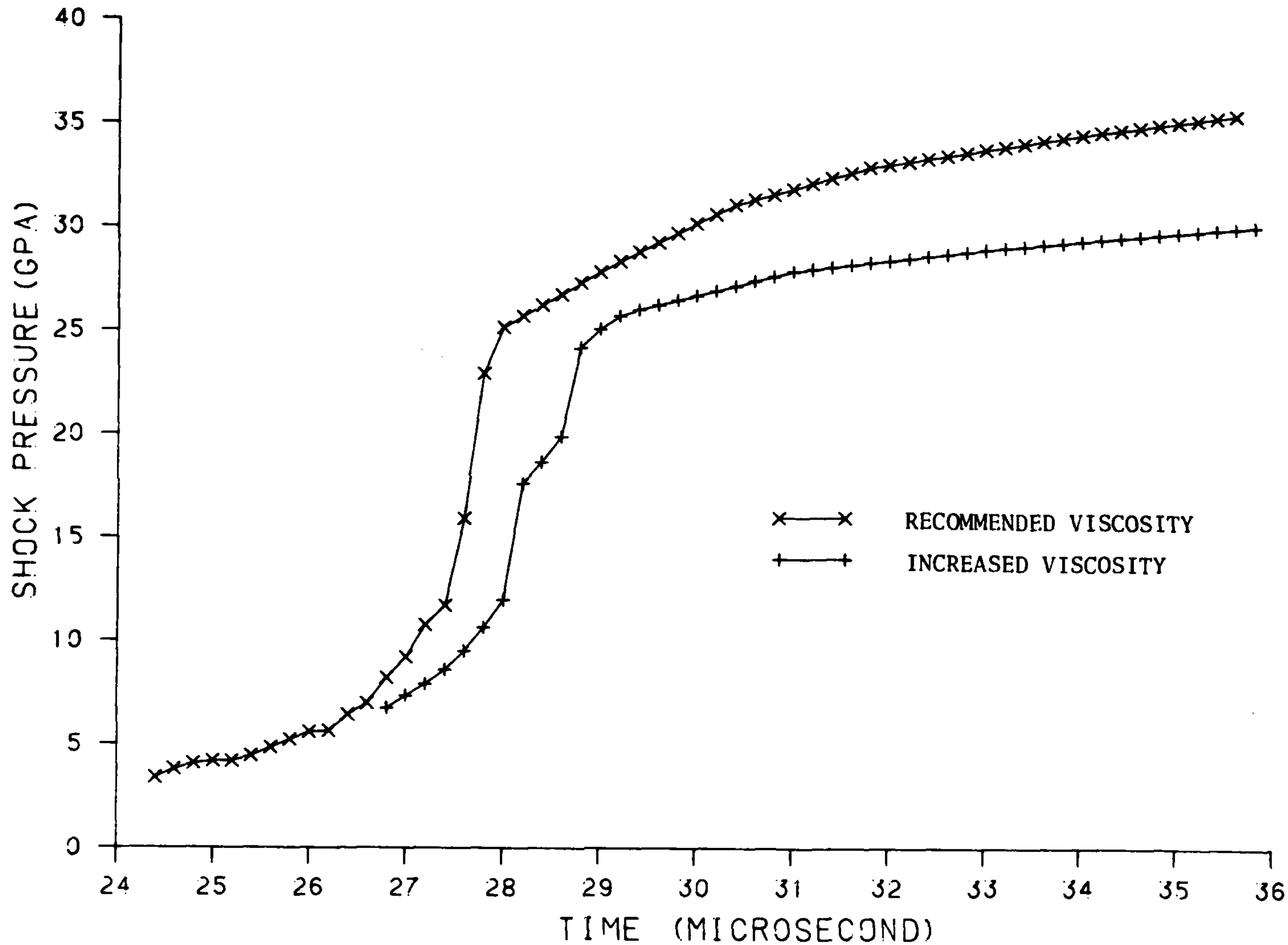


Figure 13. Effect of Artificial Viscosity Increase on Interround Detonation Propagation Computation

Since reduction of the pressure to acceptable levels does not suppress initiation, the assumption that this problem can be modeled accurately enough in two dimensions must be called into question. The two-dimensional model consists of a pair of infinitely long cylindrical rounds, one of which is initiated along an infinite line. In fact, real rounds are of finite length and donors are initiated at a point. Thus the longitudinal curvature of the donor detonation and casing acceleration as well as the influence of rarefactions which issue from the upper and lower ends of the acceptor are not included. This may be sufficient to explain the difference between the computations and experimental observations. Nonetheless, it should be noted that sympathetic detonation can still be suppressed by decreasing the energy of the donor, the sensitivity of the acceptor or both.

VI. SUMMARY

The two-dimensional numerical simulation of the problem of interround propagation of detonation revealed a very complex flow field. We found that for rounds in contact or separated by a shield completely filling the space between them, the principal shock entering the acceptor was directly transmitted from the donor detonation,while for configurations including air/spaces the principal shock was impact generated and had greater strength.

The results indicate that, in general, far-side initiation of the donor represents a worst case. This is a realistic representation of the process by which detonation transfer occurs in mass detonation. For rounds separated only by an air space, the shock initiation hazard is maximum at an intermediate interround separation. Inert computations with a thin plastic shield showed the remarkable effectiveness of the shield in reducing the shock loading on the acceptor. Reactive computations showed the process of buildup to detonation and indicated that a shield which completely fills the gap and eliminates normal impacts affords the greatest protection. When the explosive sensitivity is sufficiently reduced, the acceptor is no longer initiated along the centerline by buildup of the principal shock. Rather, initiation occurs at a point along the rear casing interface where shock reflection has raised the pressure sufficiently.

Since 2DE is known to produce results which compare well with experiments when the geometry is accurately represented, its failure to predict protection of the acceptor, even when the artificial viscosity problems were corrected, is most likely due to the overly severe loading associated with a two-dimensional representation of the problem. We feel that prediction of acceptor protection would greatly enhance our ability to assess shielding effectiveness and the effects of parameter variations and that this can be obtained by considering a less energetic donor and/or a less sensitive acceptor.

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